To appear in AJ Dec. 2003

Neutral Hydrogen Mapping of Virgo Cluster Blue Compact Dwarf Galaxies

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ABSTRACT

A new installment of neutral hydrogen mappings of Blue Compact Dwarf galaxies, as defined by optical morphology, in and near the Virgo cluster is presented. The primary motivation was to search for outlying clouds of H I as potential interactive triggers of the enhanced star formation, and therefore the mapped galaxies were selected for large H I mass, large optical diameter, and large velocity profile width. Approximately half the sample proved to have one or more small, low column density star-free companion clouds, either detached or appearing as an appendage in our maps, at resolution of order 4 kpc. Comparison is made to a sample of similarly mapped field BCD galaxies drawn from the literature; however, the Virgo cluster sample of mapped BCDs is still too small for conclusive comparisons to be made.

We found, on the one hand, little or no evidence for ram pressure stripping nor, on the other, for extremely extended low column density H I envelopes. The H I rotation curves in most cases rise approximately linearly, and slowly, as far out as we can trace the gas.

Subject headings: Galaxies: Irregular; Galaxies: Intergalactic Medium; Radio Lines: Galaxies

1. Introduction

Although there are examples of Blue Compact Dwarf (BCD) galaxies which appear optically to consist of a current starburst with no underlying population of older stars (Thuan, Izotov & Lipovetsky 1997; Brosch, Almoznino & Hoffman 1998; Hunter & Thronson 1995, e.g.), the majority of BCDs consist of an intense starburst embedded in a low surface brightness (LSB) envelope of previous generation stars (Kunth, Maurogordato & Vigroux 1988; Papaderos et al. 1996; Deeg, Duric & Brinks 1997; Almoznino & Brosch 1998). For a general review of BCDs and the possibly related H II galaxies, see Kunth & Östlin (2000). For our purposes, the term "BCD" refers to galaxy morphology regardless of galaxy size or luminosity, in the spirit of the morphological classification in the Virgo Cluster Catalog (VCC) of Binggeli, Sandage & Tammann (1985). The collection of BCDs in the VCC, even after objects with later-determined redshifts that place them in the background of the cluster are removed, is admittedly a heterogeneous sample; however, it is useful to consider the set as a whole before finer distinctions are drawn among the objects.

One important question is how the size of the optically luminous region compares to the H I envelope; what fraction of the H I reservoir is involved in the starbursts, present or past? The H I profile widths from single beam Arecibo data for the VCC BCDs are consistent with those for Sm and Im galaxies of the same total luminosity, but the optical diameters of the BCDs are smaller by a factor of 2 or 3 (Hoffman et al. 1989). We would like to know if the H I is similarly concentrated by comparison to other irregular galaxies of similar total mass. In particular, prior observations have not told us what fraction of BCDs have H I extents greatly exceeding the diameter of the region that has formed stars [pertinent to the question of whether or not H I envelopes of BCDs contribute significantly to the Lyman Limit Systems (LLS) seen in absorption in QSO spectra]; in those cases where the H I does exceed the optical extent by more than a factor of 2 it is still not clear whether the outlying gas is primordial and still infalling, distended by a blow-out from the central star-burst, or due to tidal interactions or ram-pressure sweeping.

H II galaxies are identified by pronounced optical wavelength emission lines similar to those from Galactic H II regions while BCDs are identified by their morphology in photographic images (and we exclude from consideration those BCDs which were subsequently found to have redshifts that place them far in the background of Virgo). Identification solely by emission lines also produces a heterogeneous set of objects, and one point of inquiry is to what extent the two sets (BCDs and H II galaxies) overlap. Are external interactions responsible for the starbursts, either in the form of infalling H I clouds or tidal interactions with other nearby galaxies? The latter question has been addressed by H I mapping with various resolutions, mainly for field BCDs and H II galaxies (van Zee, Skillman & Salzer

1998; Brosch, Almoznino & Hoffman 1998; Taylor, Brinks & Skillman 1993; Taylor et al. 1995, 1996a, e.g.), with largely inconclusive results. The BCDs in and around the Virgo cluster are particularly interesting in this regard, since they are distributed among the several groups and subclusters, presumably at different stages of interaction with the rest of the cluster. Are there subtle tidal effects due to the neighboring galaxies or due to the group potential, even though no evidence of dependence of star formation rates on Virgocentric distance can be found (Almoznino & Brosch 1998)? An effective strategy for assessing the prevalence of this phenomenon is to use Arecibo Observatory [1] for cursory mapping of the surroundings of all VCC BCDs with redshifts in the range of the Virgo Cluster. Only 6 of the 35 VCC BCDs (with redshifts in the Virgo Cluster range) have mapping reported prior to this paper (Hoffman et al. 1996; Brosch, Almoznino & Hoffman 1998; Lake, Schommer & van Gorkom 1987). Here we add Arecibo mapping for another five, an installment toward a sample sufficiently complete to answer the questions raised above.

The objects found to have outlying emission in our Arecibo mapping are primarily those with the largest optical diameters, the largest single-beam H I fluxes, and the largest H I profile widths. Consequently we undertook to extend the sample of VCC BCDs mapped at the Very Large Array [2] to include the 5 largest BCDs (along with one smaller object for which Arecibo mapping indicated outlying gas and one BCD in Leo). We sought to integrate long enough to acquire detailed mapping of the outer regions of the H I disk down to a column density N_{HI} of a few $\times 10^{19}$ cm^{-2}. The low spatial resolution mapping at Arecibo was designed to look for any very extended H I appendages down to even lower column density. Ionization of hydrogen by extragalactic UV is thought to be important only for $N_{HI} < 2 \times 10^{19}$ cm^{-2}, and recent detections of "Mini-High Velocity Clouds" with peak column densities well below 10^{19} cm^{-2} (Hoffman, Salpeter & Pocceschi 2002) may suggest even lower critical column densities for ionization. A significant contribution to low redshift LLS from BCDs would be detectable. Our velocity range should have been adequate to detect any outlying H I clouds (or H I-rich, optically faint dwarf companions) associated with these galaxies, should they exist.

In Sect. 2 we give the details of the Arecibo mapping, and the VLA parameters follow in Sect. 3. The results from both sets of observations are presented in Sect. 4, along with a comparison of the maps for objects mapped at both observatories. A few preliminary theoretical considerations are discussed in Sect. 5, followed by conclusions and a summary

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[1] The Arecibo Observatory is part of the National Astronomy and Ionosphere Center, which is operated by Cornell University under a management agreement with the National Science Foundation.

[2] The Very Large Array of the National Radio Astronomy Observatory is a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc.

in Sect. 6.

2. Arecibo Observations

Our mapping of the environs of five Virgo cluster BCDs was conducted as a commissioning phase project at the upgraded Arecibo Observatory in July/August 1998. We used the Gregorian feed system with the "L narrow" receiver in total power (position-switched) mode, with 6.10 kHz (about 1.3 km s^{-1}) channel spacing. Calibration was accomplished by observing several continuum sources from the VLA calibrator list, chosen to have small size compared to the $3\farcm2$ beam. In addition, we reobserved several spiral galaxies for which we had high signal-to-noise pre-upgrade H I measurements and which were known to be $\ll 3\farcm2$ in extent.

Each BCD was mapped with pointed ON/OFF observations at the optical center and in a hexagon spaced $3\farcm2$ away. The orientation of each hexagon is given by the axis-crossings of the spectra in Figs. 1 and 2. One object, Mk 1263 = FS 32 (i.e., number 32 in the list presented by Ferguson & Sandage (1990)), was also observed at positions twice as far out from the center. For the most part, we observed each point in a single 5 min (ON) scan, but each point around VCC 0022 was observed for twice that amount of time. Since these observations spanned sundown and the tie-down system at Arecibo had not yet been brought on-line, baselines were not always as smooth as users have come to expect for nighttime observations. None of the mapped objects was extended enough for sidelobes to contribute significantly to the $3\farcm2$ ring, but the $6\farcm4$ points around Mk 1263 may be receiving some sidelobe emission from the center.

For each spectrum, we removed a low-order polynomial baseline and measured the flux integrated over the full width of the feature and the profile widths at 50%, 80% and 20% of the peak of the spectrum. The results for the central spectrum are reported in Table 1, along with the systemic heliocentric velocity V_{sys} defined to be the midpoint between the 50% points on opposite sides of the central spectrum. We estimated a total flux for each galaxy by integrating spatially over the galaxy as detailed in Hoffman et al. (1996). The type listed in Table 1 is that recorded for each galaxy in the NASA/IPAC Extragalactic Database [3] (NED).

[3]The NASA/IPAC Extragalactic Database is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

3. VLA D Array Mapping

We selected as candidates for VLA mapping all VCC BCDs with H I flux > 2.0 Jy-km s^{-1}, optical diameter $D_{opt} > 0\farcm6$, and single beam profile width $\Delta V_{50} > 100$ km s^{-1}, a total of 5 objects. Adding one smaller object and one object in the Leo group, both known from Arecibo mapping to be extended, brought us to a total sample of 7 BCDs for which we sought high dynamic range D array mapping. In all, the VLA-mapped VCC BCDs are brighter in B_T by 1.2 mag, larger in optical diameter by a factor of 1.7, and brighter in H I flux by a factor of 4.0 than the VCC BCDs that have not yet been mapped. H I spectral line mapping using 27 antennas in the D array of the Very Large Array was conducted on 1999 May 28-30. Observational details are given in Table 2. Online Hanning smoothing was employed, and calibration was accomplished using sources 1219+285 (B1950) and 3C286 from the VLA calibrator list. The data were calibrated and editted using standard tasks in the Astronomical Image Processing System (Classic AIPS). Continuum subtraction was done in the *uv* plane via UVBAS, and maps were made and CLEANed using IMAGR with zero-spacing fluxes estimated from our Arecibo map and with robustness set equal to 0. After imaging, the data cube was corrected for the VLA primary beam.

The Mk 1263 field in fact contained four galaxies within the VLA primary beam: the BCD Mk 1263 itself, the Sm-ImIV pair CGCG 66-29 = FS 35 and FS 36, and (near the edge of the primary beam) the SA(s)c galaxy NGC 3389, all within the observed velocity range. Results are presented for three of the four (FS 36 was not detected; see Sect. 4.2.1). VCC 0010, 0024, 0172, 0459 and 1437 were all isolated within their primary beams, but the VCC 0340 field also contained VCC 0329, a 16.8 mag (B) ImV? galaxy, and VCC 0379, a very faint galaxy of uncertain morphology with no previous redshift measurement of any kind. To our surprise, both VCC 0329 and VCC 0379 were detected in this field.

For each of the galaxies in the seven VLA fields, we display in Figs. 3-24 a velocity-integrated H I emission map (contours) superimposed on a greyscale optical image from the Digitized Sky Survey (hereafter DSS), a velocity field from the first moment of the cube, and a panel of contour maps of the individual channels bearing significant flux. The spatially-integrated spectra are displayed in Fig. 25.

4. Results

4.1. Arecibo Results

We mapped 5 BCDs at Arecibo. Significant emission was seen in beams $3'.2$ away from the center in 3 of those cases (Mk 1263, VCC 0024 and VCC 1437); in 2 cases (Mk 1263 and VCC 0024) there is a clear velocity separation between points $3'.2$ from center on opposite sides of the galaxy, suggesting a rotating disk at least $2'.0$ in diameter. In VCC 1437 we also detect emission on opposite sides of the galaxy, but the Arecibo data alone does not give evidence of rotation. We will discuss VCC 1437 further in Sect. 4.5. Spectra from the several observed points around each galaxy are shown in Fig. 1 (for Mk 1263) and Fig. 2 (for the other 4 BCDs). Four more Virgo BCDs have pre-upgrade Arecibo mapping (to lower sensitivity) by us (Hoffman et al. 1996); 2 of these (VCC 0340 and VCC 0459) gave signs of being extended to a significant fraction of the Arecibo beam and 2 did not (VCC 0010 and UGC 7354). None of the objects appears disk-like on the POSS-II films.

4.2. VLA Results

All seven BCDs mapped at the VLA proved to be extended compared to the D array synthesized beam, with H I envelopes that extend well beyond the regions where stars have formed. The main disks of all of the objects exhibit solid body rotation, i.e., their rotation curves rise linearly as far as we can trace the gas, far outside the region of high optical surface brightness. Comparison to other (non-BCD) dwarf irregular galaxies is made in Sect. 5.3. Three of the BCDs (Mk 1263, VCC 0172 and VCC 0459) have reasonably symmetric H I disks, but four of the objects (detailed below) displayed appendages which might be tidal flares, gas blown out of the disks by multiple supernovae, or distinct infalling clouds as detailed below. D array resolution is not adequate to allow us to distinguish which possibilities are more likely in any of the four cases. Nor are we able to tell if the outer parts of these galaxies, aside from the apparent appendages, are irregular at more resolved angular scales. Results for the detected galaxies are tabulated in Table 3, which has the following columns: galaxy name, assumed distance, type as listed in NED, H I flux integrated over velocity and the spatial extent of the galaxy, the corresponding H I mass, H I diameter of the 10^{20} cm^{-2} contour on the integrated map in arcmin and kpc, the gradient of the rotation curve averaged over the approximately linear portion of the rotation curve (for BCDs only), H I mass to blue luminosity ratio, and H I to optical diameter ratio.

4.2.1. The Mk 1263 field

Within the primary beam field centered on Mk 1263, we also detected emission from the Sm galaxy CGCG 66-29 and the SA(s)c galaxy NGC 3389 (at the edge of the field). Emission from the BCD Mk 1263 and from NGC 3389 appears disklike. The H I disk around Mk 1263 is misaligned by nearly 45° from the high surface brightness optical portion of the galaxy visible on the DSS (Fig. 3). The rotation curve is approximately solid body in form. The emission-bearing channel maps are displayed in Fig. 4.

The H I disk around NGC 3389 is reasonably normal for a galaxy of its type; since the galaxy lies very near the edge of the primary beam field, we cannot determine whether the apparent appendage to the South of the H I disk in Fig. 5 is real or due to noise. Channel maps are presented in Fig. 6.

In Hoffman et al. (1996), we attributed emission seen with the Arecibo beam to the South of CGCG 66-29 (called FS 35 in that paper) to the ImIV galaxy FS 36. The VLA results shown in Fig. 5 forces us to alter that interpretation. There is a cloud of H I to the South of CGCG 66-29, but it is displaced about $3'$ to the SW of FS 36 — further from FS 36 than FS 36 is from CGCG 66-29. There is a more irregular apparently detached H I cloud a similar distance N of CGCG 66-29. The two galaxies are $2\farcm7$ apart, at projected separation 19.9 kpc assuming a distance of 25.4 Mpc for the group (allowing for Virgocentric infall). The nearest large galaxy is NGC 3389, $13\farcm9$ to the NW, at projected separation 103 kpc. We are not aware of any intragroup medium having been detected in X-ray. Some form of tidal interaction therefore seems the most likely explanation for the two detached H I clouds, although it is difficult to envision a detailed tidal scenario which would completely strip FS 36 of its gas while also drawing out the northern tail (and perhaps the SW cloud as well) from CGCG 66-29.

4.2.2. The Virgo BCDs

IC 3017 = VCC 0010 has an appendage to the SW, perpendicular to the major axes of both the optical image and the main H I disk, at velocities ~ 70 km s^{-1} below the systemic velocity. The main H I disk is reasonably well aligned with the optical image in Fig. 9 and displays quasi-solid-body rotation (rotation velocity rising nearly linearly as far as we can trace the gas). Channel maps are shown in Fig. 10. An H band image is available in Gavazzi et al. (2003).

VCC 0024 has a main H I disk well aligned with the optical image as shown in Fig. 11, but at each end there is a flare of H I kinked 20° from the major axis, with a shallower scale

length. There is, in addition, an apparently separate, small H I cloud with small velocity dispersion $2'.2$ (12 kpc) to the north, 50 km s^{-1} below the systemic velocity of the galaxy. It is not clear, from D array observations alone, whether the flares are simply warps in an extended disk, tidal flares, or distinct clouds. The rotation curve is approximately solid-body in form, rising linearly to the end and continues smoothly through the flares. The small cloud to the north is detected at $\sim 5\sigma$ and can be seen most clearly in the 1237 km s^{-1} panel of Fig.12, where there is a hint that there may be a low column density bridge to the main disk. Images in B, V, and K are available in Gavazzi et al. (2003).

VCC 0172 exhibits a relatively unremarkable H I disk with no distinct appendages or detached clouds evident above our detection threshold, around 2×10^{19} cm^{-2}. The rotation curve appears to flatten on the NW end of the disk but not (as much) on the SE end. The integrated H I map and velocity field are shown in Fig. 13, channel maps in Fig. 14. Gavazzi et al. (2003) offer an image in H band. Brosch, Heller & Almoznino (1998) describe the Hα morphology as "C+E" meaning that there is one or more prominent star formation regions near the center of the galaxy and one or more near the outer edge.

VCC 0340 has a small, apparently distinct cloud just off the end of the major axis of the H I disk, $1'.3$ (7 kpc) N of the center of the galaxy. The cloud has velocity 60 km s^{-1} higher than the galaxy's systemic velocity and very small velocity dispersion, and is unresolved by the D array. At 5σ, it also begs confirmation. The velocity field is complex, with some indications of tumbling about an EW axis but without a simple pattern. An H band image is available in Gavazzi et al. (2003). The ImV dwarf VCC 0329 was detected near the edge of the primary beam field; our H I map and velocity field are shown in Fig. 17, with channel maps in Fig. 18. In the same primary beam field, there is a newly discovered (by us, in these D array observations) H I cloud around VCC 0379, a 17.0 mag LSB typed ? by Binggeli, Sandage & Tammann (1985). The details are shown in Figs. 19 and 20.

4.2.3. VCC 1437 and a Possible Accreted Gas Cloud

VCC 1437 = Mk 772 exhibits a disk in solid body rotation, but then has an obvious appendage to the NW at a velocity close to the systemic velocity, 20 km s^{-1} lower than the velocity of the W end of the main disk. D array mapping suggests, but not conclusively, that this is a distinct cloud. Prior C array mapping by Lake, Schommer & van Gorkom (1987) was evidently not deep enough to detect the appendage. Since the cloud is unresolved by the D array beam its diameter is < 5 kpc and it has a small velocity dispersion. The integrated H I mass is 4×10^6 M$_\odot$ assuming a distance to VCC 1437 of 19 Mpc. That makes the cloud very much comparable to the Compact High Velocity Clouds (CHVC) observed around the

Milky Way, if the CHVC have distances of order 150-200 kpc (Burton, Braun & de Heij 2002). Images of VCC 1437 in H and Hα are shown in Gavazzi et al. (2003), and Vílchez & Iglesias-Páramo (2003) contribute spectroscopy leading to chemical abundances for the galaxy. Those results, along with the significant H I disk we have found, render the E: type, recorded in the RC3 (de Vaucouleurs et al. 1991) and repeated in NED, highly suspect.

4.3. Comparison of Arecibo and VLA Mapping

In Table 4, results from the VLA mapping are compared with those from Arecibo mapping for objects in common in the two samples. The compared quantities are: (1) the diameter of the H I envelope, measured to the outermost point at which we can detect the gas with each instrument, converted to kpc using the distance as given in Table 3; (2) the H I velocity profile width (FWHM), ΔV_{50}, in km s^{-1}; and (3) the integrated H I mass M_{HI} in units of 10^8 M$_\odot$. The final column gives the ratio of indicative dynamic mass $M_{ind} = V_{rot}^2 R/G$ to H I mass, using radii measured from the VLA maps, profile widths from Arecibo (since we have better velocity resolution in that data) and H I masses from Arecibo (since the single dish has better sensitivity to outlying diffuse gas). Since the optical images are too asymmetric to determine inclinations reliably, and the velocity fields in the H I maps are too irregular to allow us to determine kinematical inclinations, we took $\sin^2 i = 2/3$ for all BCDs.

In all cases save VCC 0172 (for which emission was found only in the central beam at Arecibo) and VCC 0024, the Arecibo diameter measurement is larger than the VLA measurement. This is expected, since Arecibo is more sensitive to diffuse emission and can reach lower column densities in the allotted time than the VLA. However, the Arecibo diameters are not *much* larger, only by a few percent in most cases and never more than a factor of 2. Similarly, the H I masses are larger in the Arecibo maps by only a few percent in most cases. This suggests that the H I envelopes are only a little larger than shown in the VLA maps. The Arecibo and VLA profile widths are comparable, within the resolution of the VLA maps for the most part. Since the rotation curves in the VLA maps mostly rise linearly as far as the VLA can trace the gas, this comparision confirms that outlying gas does not contribute greatly to the integrated profile.

With the single exception of VCC 0340, all BCDs mapped with the VLA have M_{ind} significantly larger than the total mass of gas plus stars could be for any reasonable stellar mass-to-light ratio. The W' cloud, of which VCC 0340 is a member, is a region of enhanced H I deficiency (Sanchis et al. 2002), so one possibility is that VCC 0340 has suffered more ram-pressure stripping than the other BCDs in our sample. That would remove gas

preferentially from the outskirts, reducing both the measured H I diameter and the velocity profile width, artifically reducing M_{ind}. The otherwise large values of M_{ind}/M_{HI} suggest that these BCDs have considerable dark matter halos.

5. Discussion

5.1. Breakdown of Virgo BCDs by Cloud Membership

The Virgo cluster is comprised of a number of subclusters, and superimposed on the cluster proper are a couple of clouds thought to lie at a distance larger by about a factor of two (Solanes et al. 2002; Gavazzi et al. 1999; Binggeli, Popsecu & Tammann 1993). These background clouds (M and W) contain a significant number (14) of the 35 VCC BCDs, according to the membership assignments of Binggeli, Popsecu & Tammann (1993). Of the 10 Virgo BCDs that have been mapped to date, 4 (VCC 0144, 0172, 0324 and 0468) are members of the W cloud, one (VCC 0340) is a member of the W' cloud which is thought (Binggeli, Popsecu & Tammann 1993) to lie between the W cloud and the Southern Extension of the Virgo cluster, two (VCC 0010 and 0022) are members of the M cloud which is the other background cloud, one (VCC 1437) is a member of subcluster B (formerly the S' cloud, roughly centered on M49), one (VCC 0459) is a member of subcluster A (associated with M87), and VCC 0024 is a member only of the cluster at large, not of any distinct subcluster or cloud. The W, M and W' clouds also have an enhanced ratio of BCDs to dwarf irregulars (dI) as a whole (types Sdm, Sm, Im, BCD and uncertain, as assigned in the VCC): 12/28 (43%), 2/4 (50%) and 2/6 (33%) respectively (16/38 or 42% overall). In contrast, the A and B subclusters along with galaxies assigned only to the cluster at large have BCD to dI ratio 19/110, or 17%.

The W and M cloud BCDs, as a group, have significantly smaller H I angular diameters than the BCDs affiliated with subclusters A and B and the cluster at large. Only one (VCC 0172) of the W+M cloud BCDs has an H I diameter (at column density $\sim 10^{19}$ atoms cm^{-2}) much in excess of $2'$ while 2 of the 3 BCDs affiliated with subclusters A and B or the cluster at large have extents well above $2'$. The W' BCD has as small an extent as any of the BCDs, however. Since we chose objects for mapping based on large H I mass and large optical diameter, definitive results must await mapping of a larger sample. However, while there is no doubt considerable spread in the intrinsic H I extents, these results are consistent with the W+M cloud BCDS being more distant by a factor of 2 as suggested by the Tully-Fisher relation applied to the larger members of those clouds (Solanes et al. 2002; Gavazzi et al. 1999). We do not see any more nor less tendency toward H I morphological peculiarities (e.g., appendages or spurs, outlying clouds, unusual velocity fields) in the W+M

cloud BCDs than in the nearer sample.

5.2. Outlying H I and Lyman Limit Systems

Table 3 indicates that H I diameters D_H are larger than optical diameters D_{25} in every measurable case, but not enormously larger. The mean of the ratio D_H/D_{25} for the 6 VCC BCDs is 3.29 with a standard deviation of 1.59 (standard deviation of the mean 0.65) and a median of 3.0. The sample spans a range of 1.53 to 6.19 in the ratio. By comparison, the 51 objects in our "field" sample from the literature (see Table 5) have a mean of 3.44 with standard deviation 2.37 (standard deviation of the mean 0.34) and a median of 2.5, spanning the range 0.5 to 9.3. Admittedly, both the H I and optical diameters for the field sample are less homogeneously measured. Still, we have no evidence for any significant difference in this ratio. This suggests that the Virgo BCDs–or this subsample at any rate–have not undergone any significant ram pressure stripping, since that would have removed some of the outermost gas.

BCDs are in general fairly rare in comparison to dI galaxies, which have already been shown to have insufficient outlying gas to account for the numbers of Lyman Limit Systems observed at higher redshift (Corbelli, Salpeter & Bandiera 2001; Dodorico & Petitjean 2001). Since D_H/D_{25} is not *extremely* large for BCDs, these relatively rare objects are not good candidates for higher redshift Lyman Limit Systems either.

5.3. Rotation Curves and Comparison with dI Galaxies

The velocity fields for Mk 1263, IC 3017, and VCC 0459 have relatively evenly spaced contours suggesting that the rotation curves of these galaxies rise linearly, in solid-body fashion, as far as we can trace the gas. The outermost contours for VCC 0024 are much more widely spaced than those inside, which might be taken as an indication that the rotation curve is beginning to flatten. However, the evident warp in the H I map complicates the issue. VCC 0340 is too poorly resolved and too complex for us to say much about its rotation curve. VCC 1437 is in solid-body rotation to the edge of the disk on both ends of the major axis, but then falls abruptly back to the central velocity on the northwest end. We interpret this to be an infalling cloud, as discussed in Sect. 4.2.3 above, and not a turnover in the rotation curve of the disk itself. On the southeast end the H I velocity field map also suggests a turn back toward the central velocity, but we have poor signal-to-noise in that beam. In all cases, however, we have only a few beams spanning the H I disk. Beam-smearing of these

rotation curves must be significant. It is unlikely, in particular, that we could identify a kink within the central arcmin or so of any of the galaxies. In spite of those complications, we have attempted to estimate an average rotation curve gradient (up to an unknown factor of $\sin i$) over the approximately linear portion of the rotation curve. The values, listed in Table 3, span the range 0.003-0.016 km $s^{-1}pc^{-1}$ with a median of 0.008 km $s^{-1}pc^{-1}$. By way of comparison, the Hα velocity fields for field BCDs obtained by Petrosian et al. (2002) have generally steeper central gradients: their range is 0.027-0.543 km $s^{-1}pc^{-1}$ with a median of 0.080 km $s^{-1}pc^{-1}$, ten times larger than ours. Whether the Hα gradients reflect orderly rotation or highly non-circular motions in the vicinity of the region of active star formation is unclear, however.

References to H I maps of field BCDs and related objects are collected in Table 5. In many cases, the velocity fields are so irregular or the spatial resolution so poor that the authors do not attempt to derive a rotation curve. We have, however, attempted to characterize the published velocity fields as to whether the rotation curve is linearly rising to the outermost point at which any semblance to regularity remains, or flattens out on one or both sides of the major (kinematical) axis. Of the 42 cases in which a velocity field is shown, 13 appear to be approximately solid body, 10 remain linear on one side of the major axis but flatten on the other, 18 flatten on both sides, and one appears to be an ongoing merger of 2 clouds. Two general features are important for comparison with dIs and the discussion in Sect. 5.4 which follows. (*i*) While in most cases the angular resolution is not small compared to the size of the region where star formation is important, the slow rise of the linear portion of the rotation curve makes it clear that the rotation velocity must be quite small over that region. However, (*ii*) the rotation velocity rises to an appreciable value, of order 50 km s^{-1}, in the well-resolved outermost regions of the H I disk. This is comparable to the maximum velocities reached in the optical velocity fields of Petrosian et al. (2002).

Typical dI galaxies with H I mapping reported in the literature mostly have rotation curves that rise linearly and somewhat rapidly in the central regions, then kink to a shallower slope. For example, in Swaters (1999) rotation curves for 62 late-type dwarf galaxies are shown. Of these, 51 have rotation curves that are kinked, clearly steeper in the central regions than in the outskirts of the disk. Only eleven have rotation curves that appear linear as far as they can be traced. Two general features for dI are: (*i*) star formation extends well beyond the kink in the rotation curve, i.e., to regions where the rotation velocity is already of order the maximum value, and (*ii*) this maximum value is typically of the same order as for BCDs, $\sim$ 50 km s^{-1}.

5.4. Dark Matter Distribution and Instabilities

For dI there is still a little controversy about the detailed shape of the rotation curve in the innermost region (Marchesini et al. 2002; Swaters et al. 2003), but there is agreement that this region is small compared to where most of the gas and stars are found and that appreciable rotation velocities are reached in those outer regions. The dark matter mass thus greatly exceeds the baryon mass and, even if there were strong starbursts in the central regions, dynamical instabilities are unlikely.

For BCDs one has to make a distinction between the inner and outer regions when considering questions of "blowup" and "blowout" (Dekel & Silk 1986; Mac Low & Ferrara 1999). For the outer regions, and for the galaxy as a whole, the dark matter mass is much larger than the gas mass, and starbursts are not likely to eject much material from the galaxy as a whole. For the inner region, where the stars are, the situation is less clear. The stars are young, massive and luminous, but the total stellar mass is not very large. Since the rotation velocity is so small here, the total indicative gravitational mass is only moderately large. The resolution of our VLA D array H I mapping is not sufficient to tell whether the gas is almost as concentrated as the stars or almost uniform density over a VLA beam. If it is concentrated, the gas mass could exceed the sum of stellar and dark matter mass within the star-forming region, and a very energetic starburst could not only eject most of the gas from the inner region, but also cause a distension of the stellar and dark matter distribution. This distension is purely dynamical, somewhat as in Gerola, Carnevali & Salpeter (1983) and Navarro, Eke & Frenk (1996), but the stars and dark matter are only lifted into somewhat larger orbits. The gas, on the other hand, can fall back into the inner region after it cools. Better angular resolution H I mapping of the inner regions is clearly needed to investigate this conjecture.

5.5. Statistics on Companion H I Clouds

Several studies seeking indications of external interactions with field BCDs (or objects that would resemble the VCC BCDs on comparable plate material at a comparable distance) have been conducted (Simpson & Gottesman 2000; van Zee, Skillman & Salzer 1998; Brosch, Almoznino & Hoffman 1998; Taylor, Brinks & Skillman 1993; Taylor et al. 1995, 1996a, e.g.). Similar efforts have been made to find potential interactors that might, a few hundred My in the future, turn otherwise isolated dwarf irregular galaxies into BCDs (Pisano, Wilcots & Liu 2002; Simpson & Gottesman 2000; Pisano & Wilcots 1999; Taylor et al. 1996b). In most cases in which a distinct companion is found, careful inspection of the DSS reveals that the companion is a Low Surface Brightness galaxy. Pustilnik et al. (2001b), in a

search for *optical* companions in the vicinity of 86 BCDs from the Second Byurakan Survey, concluded that $\sim$ 80% of their sample were plausibly triggered either by tidal interaction with a companion (either larger or smaller than the BCD) or by a recent merger. Östlin et al. (2001) and Bergvall & Östlin (2002) argue on the basis of Hα kinematics that the several blue compact galaxies in their sample result from mergers of gas-rich dwarf galaxies or massive H I clouds. Detached H I clouds free of stars to the detection limit of the DSS, however, appear to be quite rare.

Most H I surveys, like the present one, have been conducted with the VLA in its lowest spatial resolution mode, the D array, and have synthesized beams not much smaller than the H I size of the BCD. Therefore, for galaxies at roughly the distance of the Virgo Cluster, a gas cloud separated from the H I envelope of the BCD by less than the H I radius of the BCD might appear to be connected to that envelope, much like the VCC 1437 cloud discussed above. We have scoured the maps available in the literature (see Table 5) for such potential clouds as well as clearly separated clouds around field objects that would resemble the VCC BCDs at a comparable distance on comparable plate material. In the vicinity of 51 field (or loose group) BCDs, we find 20 with no companion objects within $\sim$ 200 kpc; 13 with companion H I clouds (including previously catalogued galaxies) that have stars evident on the DSS or other optical images available to the authors of those maps; 12 with clearly separated, spatially unresolved, low column density H I clouds with no stars visible on available optical images; and 9 with appendages or spurs that do not appear to be tidal in nature and which might be detached from the BCD's H I envelope at higher spatial resolution. For our 6 Virgo BCDs, the corresponding numbers are 2, 1, 2 and 2. (In both sets of BCDs, some BCDs appear in multiple categories.) Our sample of Virgo BCDs is not yet large enough to say whether or not there are differences in the two distributions.

6. Conclusions and summary

We have presented Arecibo maps of five VCC BCD galaxies and VLA D array maps of six along with a field in Leo containing one BCD, a Sm-ImIV pair, and a much larger spiral. The VCC maps form an installment toward an eventual sample statistically complete enough to contrast with the growing field sample from the literature.

Of the five BCDs in the Virgo cluster and surrounding clouds mapped at Arecibo, three gave evidence of H I emission extended outside the central $3\rlap{.}'2$ beam. That increases the sample of VCC BCDs with Arecibo mapping to nine objects, with five in all showing emission outside the central beam. The extended objects were those with the largest H I masses, largest optical diameters, and largest H I velocity profile widths, and so we used

those criteria to select the six VCC BCDs for mapping with the VLA D array.

All seven BCDs mapped at the VLA are clearly extended beyond the D array beam, $\sim 45''$, and all give some indications of systematic rotation. We found two examples of kinematically distinct appendages which might resolve into distinct gas clouds at higher resolution, and two clearly detached low column density clouds (one appearing to be a Compact HVC in the process of coallescing with the galaxy's disk). In all cases the clouds are within ~ 10 kpc of the BCD.

Comparison was made to a sample of similarly mapped field BCDs (or related objects) drawn from the literature, but conclusive statements were not possible due to the small size of the Virgo sample mapped to date. However, regarding the question of starburst triggering by interactions, we note that about one-third of the BCDs in both samples discussed here do not appear to have companion H I clouds, with or without stars. Mapping of these objects at higher angular resolution, and of additional Virgo objects, is clearly indicated. Determinations of the hot (ionized) gas content in BCDs would also be very helpful in determining whether the kinematically distinct clouds are falling in or being blown out.

We have one fairly firm double negative result: There is little evidence for any appreciable mass loss due to ram pressure stripping, but also no evidence for any extremely extended H I envelope at column densities $N_{HI} < 2 \times 10^{19}$ cm^{-2}. BCD galaxies are therefore not good candidates for Lyman Limit Systems.

The H I rotation curves rise linearly and slowly all the way out for BCDs, with maximum velocity and total indicative mass comparable to those for the more common low surface brightness dwarf irregular galaxies. On the other hand, the angular momentum in the very small central star-forming region is quite small. Better H I angular resolution will be required to find out just how small the angular momentum is and to see just how concentrated the gas is.

We thank the anonymous referee for comments which helped increase the clarity of this paper. The Digitized Sky Surveys were produced at the Space Telescope Science Institute under U.S. Government grant NAG W-2166. The images of these surveys are based on photographic data obtained using the Oschin Schmidt Telescope, which is operated by the California Institute of Technology and Palomar Observatory on Palomar Mountain. The plates were processed into the present compressed digital form with the permission of that institution. The Second Palomar Observatory Sky Survey (POSS-II) was made by the California Institute of Technology with funds from the National Science Foundation, the National Geographic Society, the Sloan Foundation, the Samuel Oschin Foundation, and the Eastman Kodak Corporation.

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Table 1. Arecibo Observations

Galaxy	RA(1950) hhmmss.s	Dec(1950) ddmmss	Type	Central Flux mJy km s^{-1}	rms mJy	Total Flux mJy km s^{-1}	V_{sys} km s^{-1}	ΔV_{50} km s^{-1}	ΔV_{80} km s^{-1}	ΔV_{20} km s^{-1}
Mk 1263	104617.8	122716	BCD	5515	1.5	5600	1321	129.9	114.6	143.7
VCC 0022	120751.0	132654	BCD?	643	1.0	700	1695	51.5	33.5	69.0
VCC 0024	120803.0	120218	BCD	3902	1.5	3800	1292	197.5	181.5	214.2
VCC 0468	121846.2	42118	BCD?	880	1.7	700	1980	35.4	21.1	58.5
VCC 1437	123001.2	92654	E:	1746	1.4	2500	1148	71.0	51.1	101.8

Table 2. Very Large Array Observations

	Mk 1263	VCC 0010	VCC 0024	VCC 0172	VCC 0340	VCC 0459	VCC 1437
Date (all 1999 May)	28	29	29	29-30	30	29	29-30
Antennas	27	27	27	27	24	27	27
Pointing Center R.A.(2000)	10:49:03.0	12:09:24.8	12:10:36.2	12:16:01.0	12:19:21.8	12:21:11.5	12:32:33.5
Pointing Center Dec.(2000)	12:18:00	13:34:25	11:45:37	04:39:02	05:54:51	17:38:16	09:10:25
V (heliocentric, km s^{-1})	1340	1972	1289	2175	1560	2099	1160
Array	D	D	D	D	D	D	D
Channels	64	64	64	64	64	64	64
Channel separation (km s^{-1})	10.4	10.4	10.4	10.4	10.4	10.4	10.4
Time on source (min)	53	53	54	92	79	81	110
Beam (arcsec)	49×46	49×46	47×44	49×44	47×42	45×44	50×46
rms (mJy beam^{-1}chan^{-1})	1.2	1.4	1.3	1.0	1.5	0.9	0.9

Table 3. Very Large Array Results

Galaxy	Type	Distance	HI Flux	HI Mass	HI Diameter		Vel. Grad.	M_H/L_B	D_H/D_{25}
		Mpc	Jy km s^{-1}	$10^8 M_\odot$	arcmin	kpc	km s^{-1}pc^{-1}	$M_\odot/L_\odot$	
NGC 3389	SA(s)c	25.4	13.66	20.8	3.2	23.6	···	0.11	1.16
Mk 1263	BCD	25.4	4.69	7.14	2.5	18.5	0.008	1.46	3.61
CGCG 66-29	Sm	25.4	2.93	4.48	1.4	10.4	···	0.64	1.28
IC 3017	BCD	32.3	1.91	4.68	1.6	14.9	0.014	0.33	2.59
VCC 0024	BCD	19.0	2.50	2.13	3.4	18.8	0.016	0.87	6.19
VCC 0172	IAm?	32.3	4.72	11.6	2.5	23.4	0.008	0.66	3.53
VCC 0329	I?	26.6	0.87	1.45	0.4	3.0	···	0.69	1.20
VCC 0340	···	26.6	1.84	3.08	1.3	10.3	0.003	0.16	1.53
VCC 0379	···	26.6	1.10	1.84	1.1	8.7	···	1.05	···
VCC 0459	BCD	19.0	2.46	2.10	1.6	8.7	0.009	0.36	2.54
VCC 1437	E:	19.0	1.50	1.28	1.4	7.9	0.003	0.43	3.36

Table 4.   Comparison of Arecibo and VLA Results

Galaxy Name	D_{HI} (kpc) VLA	D_{HI} (kpc) AO	ΔV_{50} (km s^{-1}) VLA	ΔV_{50} (km s^{-1}) AO	M_{HI} ($10^8 M_\odot$) VLA	M_{HI} ($10^8 M_\odot$) AO	M_{ind}/M_{HI}
Mk 1263	18.5	~ 22	120	130	7.1	8.5	16.0
IC 3017	14.9	< 28	190	170	4.7	5.9	31.8
VCC 0024	18.8	~ 17	190	198	2.1	3.3	97.4
VCC 0172	23.4	$\cdots$	120	113	11.6	11.8	11.0
VCC 0340	10.3	~ 15	60	49	3.1	6.0	1.8
VCC 0459	8.7	~ 11	100	110	2.1	2.0	22.9
VCC 1437	7.9	~ 17	50	71	1.3	2.1	8.3

Table 5. Mapped BCDs Outside of Virgo

Observers	Date Mapped	Telescope	Galaxies	Ref
Brinks & Klein	1985	VLA B	II Zw 40	1
Cox et al.	1994&1995	VLA C&D	II Zw 70	2
Hoffman et al.	1988&1989	NAIC	UGC 7257, BTS 171	3
Kobulnicky & Skillman	1993	VLA DnC	NGC 5253	4
Meurer et al.	1992&1993	ATCA	NGC 2915	5
Meurer, Staveley-Smith & Killeen	1990&1991	ATCA	NGC 1705	6
Pustilnik et al.	1994&1995	VLA C&D	SBS 0335–052	7
Putman et al.	1996&1997	ATCA	FCC 35	8
Simpson & Gottesman	1993	VLA C	A1116+51; Haro 4, 27, 33, 36; Mrk 51, 67, 328	9
Stil & Israel	1989&1990	WSRT	NGC 1569	10
Taylor et al.	1991&1992	VLA C&D	VII Zw 8, Mrk 314, 600, Haro 26	11, 12
Taylor et al.	1992&1994	VLA D	UM 323, 372, 422, 439, 446, 452, 456, 461/2, 463, 465, 483, 491, 500/1, 504, 533, 538, 559	13
van Zee et al.	1993&1994	VLA C&D	UGCA 20	14
van Zee, Salzer & Skillman	1998-2000	VLA B&CS	Mrk 324, 750, 900, 1418; UM 38, 323	15
van Zee, Skillman & Salzer	1997	VLA B & C	II Zw 40, UGC 4483, UM 439, 461/462	16
van Zee et al.	1993&1995	VLA B&C&D	I Zw 18	17
Viallefond & Thuan	1979	WSRT	I Zw 36	18
Walter et al.	1986&1990	VLA B&C	II Zw 33	19

References. — (1) Brinks & Klein (1988); (2) Cox et al. (2001); (3) Hoffman et al. (1996); (4) Kobulnicky & Skillman (1995); (5) Meurer et al. (1996); (6) Meurer, Staveley-Smith & Killeen (1998); (7) Pustilnik et al. (2001a); (8) Putman et al. (1998); (9) Simpson & Gottesman (2000); (10) Stil & Israel (1998); (11) Taylor et al. (1994); (12) Taylor, Brinks & Skillman (1993); (13) Taylor et al. (1995); (14) van Zee et al. (1996); (15) van Zee, Salzer & Skillman (2001); (16) van Zee, Skillman & Salzer (1998); (17) van Zee et al. (1998); (18) Viallefond & Thuan (1983); (19) Walter et al. (1997)

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